Emergence of the Green's Functions from Noise and Passive Acoustic Remote Sensing of Ocean Dynamics

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LONG-TERM GOALS

- To evaluate feasibility and determine physical limits of performance of a passive acoustic system for characterization of a time-varying ocean where ambient acoustic noise is utilized as a probing signal.
- To develop a passive remote sensing technique for acoustic characterization of oceanic currents.

OBJECTIVES

1. To demonstrate theoretically emergence of the deterministic Green's functions (GFs) from cross-correlations of noise due to sources distributed in a volume and on boundaries in inhomogeneous, fluid-solid environments with dissipation.
2. To investigate a relation between the deterministic GFs and a two-point correlation function of noise in a low-frequency regime where stationary-point arguments become inapplicable.
3. To quantify degradation of performance of passive remote sensing techniques due to ocean surface motion and other variations of underwater sound propagation conditions in time.
4. To retrieve flow-induced non-reciprocity of acoustic phase and amplitude of the deterministic GFs from cross-correlation of diffuse sound fields generated as a result of scattering by inhomogeneities in the water column and/or by seafloor and sea surface roughness.
5. To determine accuracy of current velocity measurements using acoustic travel time non-reciprocity retrieved from a two-point noise cross-correlation.
6. To evaluate, for shallow- and deep-water scenarios, optimal parameters of a passive acoustic system for ocean temperature and current velocity measurements using cross-correlation of ambient noise and/or sound fields generated by sources of opportunity.

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APPROACH

This work includes theoretical research and numerical simulations of ambient noise fields. Theoretical predictions have been verified using low-frequency noise records from the North Pacific Acoustic Laboratory (NPAL) Billboard Array (Worcester and Spindel, 2005; Baggeroer et al., 2005). Experimental data have been kindly provided by Dr. P. F. Worcester and the NPAL Group (J. A. Colosi, B. D. Cornuelle, B. D. Dushaw, M. A. Dzieciuch, B. M. Howe, J. A. Mercer, W. H. Munk, R. C. Spindel, and P. F. Worcester). Our theoretical approach is based on the flow reversal theorem (Godin, 1997), which is an extension of the reciprocity principle to moving media. The approach proved to be instrumental in deriving exact representations of the noise fields and their statistics in arbitrarily inhomogeneous, moving media in terms of deterministic GFs (Godin, 2006, 2007, 2009a, 2010a). Moreover, the flow reversal theorem leads to important identities (often termed Ward identities), which relate surface and volume integrals of certain products of GFs to the GF value at a point and underlie exact and asymptotic local relations between diffuse noise cross-correlations and deterministic GFs (Godin, 2006, 2007, 2009a, 2010a).

In underwater acoustics and other geophysical applications, noise fields are often diffuse but, with the exception of thermal noise (Rytov, 1953; Godin, 2007, 2009a), are never the "perfectly diffuse" wave fields for which exact relations between noise cross-correlations and deterministic Green's functions hold. Asymptotic approaches based on the stationary phase approximation (Snieder, 2004; Godin, 2006) and its extensions (Godin, 2009d, 2010a) have been used to determine the information content of two-point cross-correlation function of acoustic noise in the ocean. The asymptotic approaches have been also used to investigate the role of a finite correlation length of noise sources and of motion of the sources on the noise cross- and auto-correlation functions. Quasi-stationary approximation (Godin, 2002) has been used to quantify effects of the sea surface and the sound speed time-dependences on feasibility of inverting noise cross-correlations for parameters of the sound speed and, especially, current velocity fields.

The key individuals that have been involved in this work are Oleg A. Godin (CIRES/Univ. of Colorado and NOAA/ESRL) and Nikolay A. Zabotin (CIRES/Univ. of Colorado). Dr. Zabotin focused on evaluation of observation times necessary for GF retrieval from diffuse noise fields in an underwater acoustic waveguide and on experimental data processing. Dr. Godin took the lead in theoretical description of long-range correlations of random acoustic fields in inhomogeneous, moving or motionless media.

WORK COMPLETED

Emergence of the deterministic GFs from cross-correlations of noise due to sources distributed in a volume and on boundaries in inhomogeneous, fluid-solid environments with dissipation has been demonstrated theoretically (Godin, 2009a, 2010a).

Degradation of performance of passive remote sensing techniques due to motion, correlation, and non-uniform distribution of noise sources has been quantified (Godin, 2009c, d).

A mechanism of formation of spurious arrivals in time-averages of noise cross-correlations has been analyzed and approaches to identifying and excluding the spurious arrivals have been suggested (Zabotin and Godin, 2010).

For use in analyses of diffuse noise fields and their possible utilization in passive acoustic characterization of the underwater environment, acoustic GFs have been studied for various scenarios of interest, in particular, for low-frequency noise sources within the ocean bottom (Godin, 2010b) and in ocean with scalar and vector inhomogeneities within the water column (Godin, 2009b).

Theoretically predicted possibility of retrieving flow-induced non-reciprocity of the deterministic GFs from cross-correlation of diffuse sound fields (Godin, 2006) has been confirmed by Monte-Carlo simulations (Charnotskii and Godin, 2010) and verified in a field experiment (Charnotskii et al., 2010).

Based on advanced theoretical analysis of the noise cross-correlation function in the ray approximation (Godin, 2009c, 2009d, 2010a), techniques have been developed to retrieve deterministic travel times from the cross-correlation function with accuracy to a fraction of the reciprocal of the data sampling frequency (Godin et al., 2010). Feasibility of passive ocean tomography with acoustic daylight has been experimentally demonstrated (Godin et al., 2010).

RESULTS

We carried out a comprehensive investigation of long-range correlations of noise fields in arbitrary inhomogeneous, moving or motionless fluids in the ray approximation (Godin, 2009c, 2009d, 2010a). We have demonstrated that the two-point correlation function of high-frequency, diffuse acoustic fields generated by smooth distributions of random sources located on a surface and/or in a volume approximates the sum of the deterministic Green's functions, which describe sound propagation in opposite directions between the two points. In arbitrary moving or quiescent, absorbing fluids with smoothly varying sound speed, mass density, and flow velocity, the approximate Green's functions contain the same ray arrivals with the same travel times as the exact Green's functions, and differ by amplitudes of the ray arrivals. Explicit relations between amplitudes of respective ray arrivals in the noise cross-correlation function and the Green's functions have been obtained and verified against specific problems allowing an exact solution. Earlier results have been extended by simultaneously accounting for sound absorption, arbitrary distribution of noise sources in a volume and on surfaces, and fluid inhomogeneity and motion (Godin, 2010a).

We developed a full-field Monte-Carlo model of generation and propagation of diffuse noise in a moving fluid. Acoustic signals generated by random sound sources and received by an array of receivers have been simulated. Deterministic acoustic travel times between receivers emerge as peaks of the envelope of the noise cross-correlation function evaluated through time-averages of products of acoustic pressures recorded at two points. In the case of moving fluids, our model shows the theoretically predicted (Godin, 2006) asymmetry in the position of the correlation peaks at positive and negative time delays, which reflects acoustic non-reciprocity and enables determination of the flow velocity vector (Charnotskii and Godin, 2010; Charnotskii et al., 2010).

To investigate the feasibility of passive acoustic tomography of the ocean, we re-examined (Godin et al., 2010) noise data obtained by the NPAL Group during the 1998–1999 Billboard Array Experiment (Worcester and Spindel, 2005; Baggeroer et al., 2005). The data have been made available for this study by Dr. P. F. Worcester. Two-point noise cross-correlation function (NCCF) has been evaluated by averaging time series of noise recorded on the five vertical line arrays (VLA1 to VLA5) that comprise the Billboard Array.

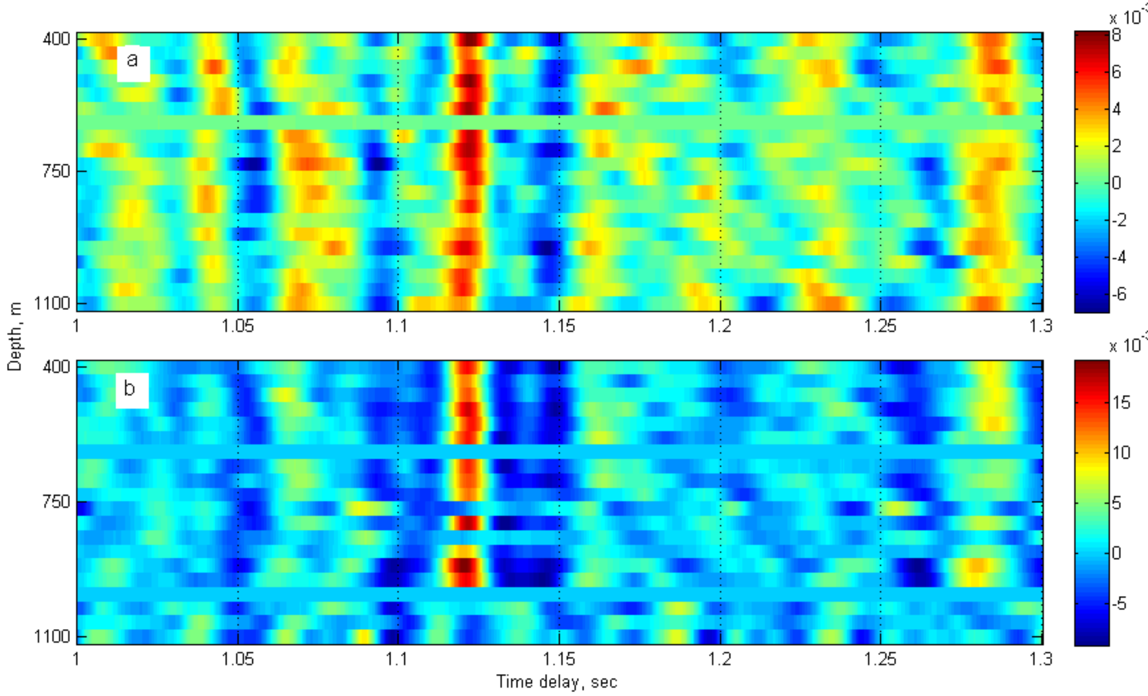

Figure 1. Suppression of transient sources of non-diffuse and non-Gaussian noise using "kurtosis screening" of the data. Estimates of the cross-correlation function of noise recorded on hydrophones located at the same nominal depth of VLAs 1 and 3 are obtained (a) without and (b) with "kurtosis screening." Noise records are averaged over 12 hours of observation. [Estimates of the noise cross-correlation function are shown as a function of time delay ranging from 1 to 1.3 sec and depth from 400 to 1100 m. In panel (a), the cross-correlation function has peaks of comparable magnitude around time delays of 1.02, 1.04, 1.07, 1.13, 1.16, 1.19, 1.24, and 1.28 sec. In panel (b), main peaks around the time delay of 1.13 sec are clearly visible for various depths.]

In individual data segments, localized, transient noise sources either of biological origin or due to nearby shipping and micro-earthquakes usually dominate over contributions of distributed noise sources, such as distant shipping and breaking water waves on the ocean surface. Statistics of the noise field at the experimental site exhibit strong deviations from Gaussianity when the field is dominated by localized noise sources (Baggeroer et al., 2005). Therefore, the contributions of localized noise sources can be suppressed, and diffusivity of the noise field can be effectively enhanced by excluding data segments with non-Gaussian noise from time averages. This concept was implemented by requiring that excess kurtosis of a time series recorded by a hydrophone not exceed a certain threshold. As illustrated in Fig. 1, the "kurtosis screening" technique eliminates or suppresses most peaks and troughs in the NCCF estimate except for the peaks and troughs in the vicinity of deterministic timefronts; helps to identify the NCCF features needed for environmental characterization; and improves the accuracy of the deterministic travel-time retrieval from the NCCF.

Oceanographically-relevant sound-speed measurements with accuracy ~1 m/s require relative accuracy of acoustic travel time measurements of about 0.1%. Accurate measurements of ray travel times can be

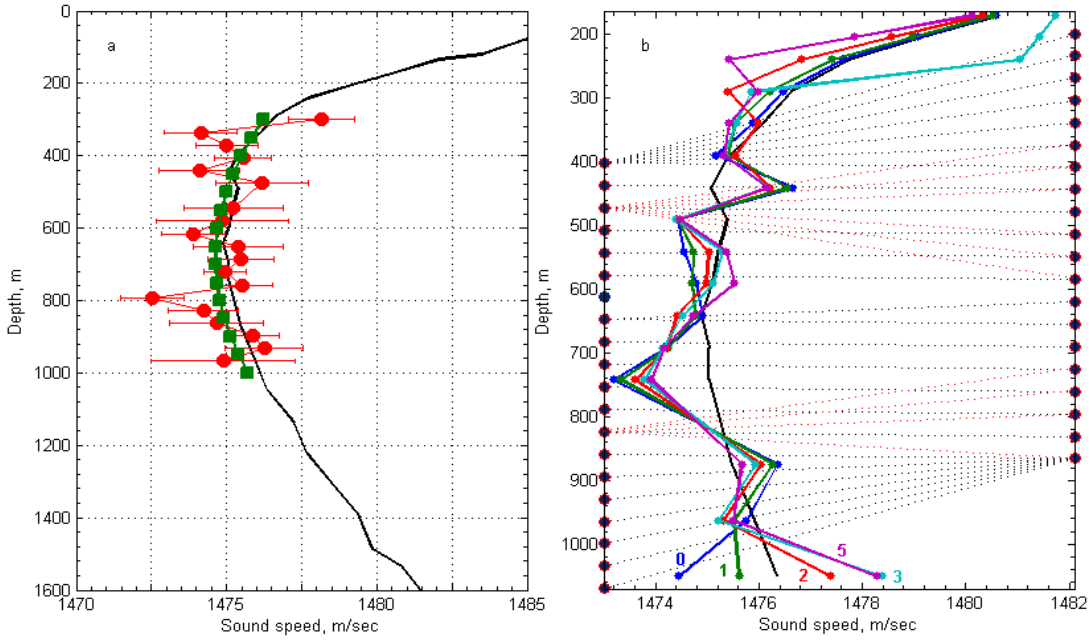

Figure 2. Inversion of passively measured acoustic travel times. Sound-speed profiles are retrieved using either a (a) simple, blind inversion or (b) full tomographic inversion of the travel times between hydrophones on VLAs 1 and 5. Annual average sound-speed profile (Worcester and Spindel, 2005) is shown by solid black lines. In panel (a), red dots with error bars and green dots show results of inversion for individual hydrophone pairs and the best-fitting parabola, respectively. In panel (b), sound-speed inversions obtained using different number of ray paths per VLA 1 hydrophone are distinguished by color.
[In panel (a), sound speed is shown as function of depth from 0 to 1600 m. The annual average sound-speed profile has a minimum of about 1475 m/s at depth of about 650 m. Error bars of the inversion results vary from 1 to 2.5 m/s and in most cases intersect the annual average profile. Smoothed inversion results (green dots) are within 0.5 m/s the annual average profile at depths from 300 to 1000 m. In panel (b), depth and sound speed range from 170 to 1070 m and from 1473.5 to 1482 m/s, respectively. Five different inversions of the sound speed profile are within 0.5 m/s from each other at all depths except for the minimum and maximum depths.]

obtained from NCCF's zero crossings (Godin 2009d, 2010a). Travel times along direct rays connecting hydrophones on various VLAs were found from the NCCF estimates as positions of those zero crossings that lie between the main peak and trough. With horizontal variation of the sound speed between VLAs being negligible, two techniques were used for retrieval of the vertical dependence of the sound speed c from passively measured travel times. In a simple, blind inversion (Fig. 2a), only travel times between hydrophones of the same number on two VLAs were used. The sound speed was calculated as the ratio of the distance between the hydrophones to the measured travel time, and assigned to the mid-depth of the hydrophones. No *a priori* environmental information is utilized in such an inversion. It can be shown that, because of relatively small horizontal separations of VLAs, neglect of the sound-speed variation along a ray leads to errors not exceeding 0.2 m/s. The inversion errors are dominated by errors in the travel-time measurement, which are caused by the difference between the NCCF and its estimate. The errors were evaluated for each hydrophone pair (Fig. 2a) from

the level of incoherent noise in the NCCF estimate relative to the contrast between the NCCF peak and trough.

A more accurate and detailed reconstruction of the sound-speed profile is provided by a full tomographic inversion (Fig. 2b). The inversion utilized up to $1 + 2N$, $N = 0, 1, \ldots, 5$ propagation paths for each hydrophone. The propagation paths for $N = 0$ are shown in Fig. 2b by black dashed lines; additional propagation paths for $N = 3$ are illustrated for two hydrophones with red dashed lines. The accuracy of the inversion is estimated from the travel-time measurement errors and the RMS mismatch between the measured travel times and their values in the reconstructed environment. In Fig. 2b, the RMS sound speed-inversion errors range from 1.5 to 1.9 m/s, depending on N. The passively measured sound speed profiles presented in Figs. 2a and 2b agree within their stated measurement errors with each other and, below 700 m, with the annual average sound speed profile.

We have demonstrated, for the first time, that acoustic daylight (i.e., diffuse noise) in the ocean can be successfully used to measure sound-speed profiles with accuracy suitable for oceanographic applications (Godin et al., 2010). Further research is needed to determine the feasibility of ocean thermometry and tomography with acoustic daylight at longer ranges of tens and hundreds of kilometers.

IMPACT/APPLICATIONS

Our theoretical and experimental results strongly suggest that a dedicated passive acoustic system can be employed for cost-effective, long-term, depth-resolving observations of variations in the temperature field and heat content in the ocean.

RELATED PROJECTS

Passive Radio Imaging for Applications in Water Resource Management, Glaciology, and Space Weather Monitoring, a one-year project funded by CIRES under its Innovative Research Program, see http://cires.colorado.edu/science/pro/irp/2009/. The project has utilized the availability of extensive digital records of radio noise in the HF band to explore the feasibility and possible applications of a radio-wave counterpart of the acoustic noise interferometry.

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